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Mapping and Structural Analysis in the Southwestern Sudbury Basin: Implications for Mineral Exploration

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Mapping and Structural Analysis in the Southwestern Sudbury Basin: Implications for Mineral Exploration

by

A.J. Dubois and K. Benn

2003

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Abstract

The work presented here is included in the Sudbury Targeted Geoscience Initiative (TGI) designed to gain a better understanding of the tectonic deformation of the Sudbury Structure, one of the world's largest Ni-Cu-PGE mining camps. The work is focussed on one of the most structurally complex parts of the structure, an area of 220 km^2 in Trill, Drury, Denison and Fairbank townships. The study area has undergone a large degree of deformation after 1850 million years ago that modified the shape of the Sudbury impact structure. This is the first detailed structural study in the western Sudbury Basin. The results are expected to provide a new framework for mineral exploration.

During the summer 2001, over 300 outcrops were mapped and oriented hand specimens were collected for microstructural analysis. According to preliminary results, the study area may be divided in three zones: 1) the northwest corner, which has not undergone ductile deformation; 2) a northeast-southwest trending zone of strongly sheared rocks that corresponds to the previously defined South Range shear zone; and 3) the southern portion of the study area that is interpreted to lie within the hanging-wall block of the South Range shear zone. Structures within the South Range shear zone indicate that the ductile shearing resulted from a south-over-north dextral oblique thrusting. Rocks in the interpreted hanging-wall block of the shear zone are deformed by anastomosing (possibly conjugate) shear zones suggesting a bulk pure shear with a vertical maximum principal stretch. Ductile deformation after 1850 million years ago may have occurred in a transpressive regime with strain partitioned between dextral oblique shearing in the SRSZ and bulk pure shear south of the SRSZ. Shear zones in the interpreted hanging-wall block are locally hydrothermally altered, suggesting fluid movements during the ductile deformation.

In 2002, the results of further mapping and petrographic studies, as well as structural logging of drill cores and the incorporation of geophysical data were used to produce geometrical and kinematic models for the study area. These results will be published in a future report.

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Introduction

The Sudbury Targeted Geoscience Initiative (TGI) is a three-year program (2000–2003) (Ames et al. 2001; Ames 2002) designed to gain a better understanding of 1) the geological setting of the world's largest nickel-copper-platinum group element (PGE) deposits, associated with the Sudbury Igneous Complex (SIC); and 2) the processes involved in ore deposit genesis and subsequent deformation. The Sudbury TGI is a collaborative project that involves the Geological Survey of Canada, the Ontario Geological Survey, mining industry partners and several universities, including the University of Ottawa.

As part of the Sudbury TGI, this study was initiated in 2001 and is an investigation of the lithologic and, especially, structural controls on nickel-copper-PGE mineralization in the SIC and its immediate footwall (Dubois and Benn 2001, 2002). This two-year project, supported by the Ontario Geological Survey and the University of Ottawa, involves extensive mapping in the southwest part of the SIC and its footwall. It emphasizes the identification, description and classification of structures related to pre-, syn- and post-SIC deformation events. The project also aims to propose possible models for the post-Sudbury event deformational history of the southwestern part of the Sudbury basin.

The area was selected for mapping and structural analysis because it has undergone a large degree of deformation after 1850 million years ago that has strongly modified the Sudbury impact structure (Shanks and Schwerdtner 1991a). This makes the study area particularly interesting for an analysis of the deformational history, and because unravelling the complex geological structure may lead to the development of new mineral exploration targets.

At the end of the project, we should be able to determine which structures accommodated the post-impact shortening of the western part of the SIC leading to apparent thrust imbrication. Products will include 1) structural profiles and three-dimensional models to show the geometries of rock units and structures in the subsurface; 2) quantification of the degree of shortening in order to better understand the original shape of the basin; and finally 3) proposal of a model for the structural evolution and the kinematic history of this part of the Sudbury Structure. These objectives will be attained by using the data collected during mapping and petrographic study, by incorporating geological and geophysical data made available by the mining industry and by application of a sophisticated software package for modelling tectonic deformations.

LOCATION, ACCESS AND MINING ACTIVITIES

The study area is located approximately 20 km west of Sudbury. It encompasses roughly 220 km^2 and includes parts of Trill, Drury, Fairbank and Denison townships (Figure 1). The southern part of the studied area is crosscut by two west to east trending main roads: the Trans-Canada Highway (highway 17) and highway 658. Three roads radiate to the north from highway 658. The westernmost road is the regular access to the Fairbank Provincial Park, west of Fairbank Lake and meets highway 144. The middle one allows access to the Crean Hill and the Lockerby mines, and to the eastern part of Fairbank Lake, a local major lake. The easternmost road trending north is closed to the public in its southern part, but is open past the Lockerby Mine and meets highway 144 further north. Many snowmobile trails and logging roads nucleate from those roads.

Rivers link lakes and swamps; they are quite small and are not navigable with canoe.

Major power lines trending east-west crosscut the area between Fairbank Lake and Worthington. Survey trails below power lines are accessible either by foot or with all-terrain vehicles (Figure 2). The area includes active and past-producing mines (*see* Figure 1) that are located on the Worthington Offset dike (Victoria Mine, Kidd Copper Mine, Totten Mine and Worthington Mine); and at the contact between the SIC and the footwall (Chicago Mine, Sultana Mine, Crean Hill Mine (INCO) and the Lockerby Mine (Falconbridge Limited)). Thousands of tons of ore were extracted from the Victoria Mine, and 3500 tons

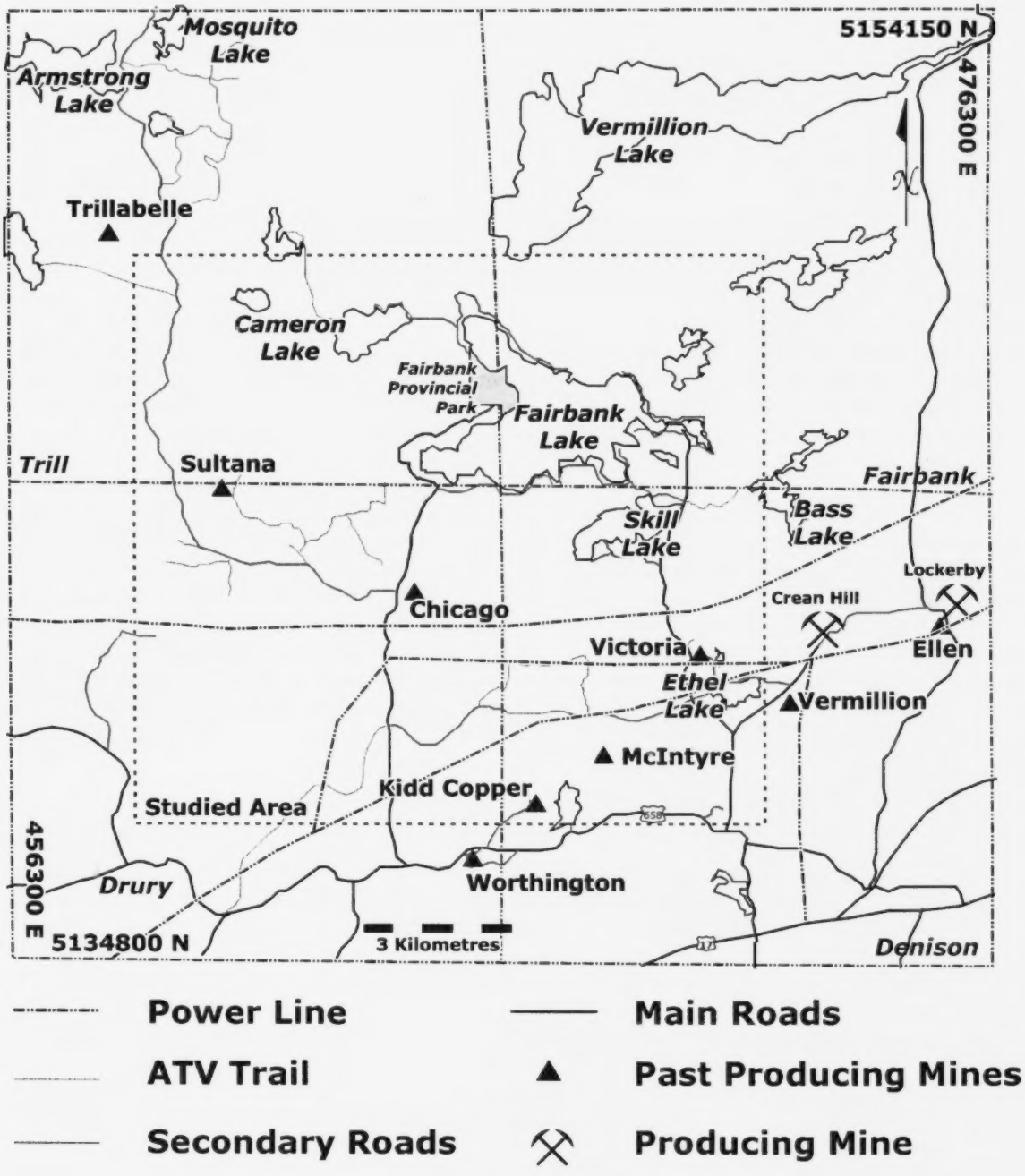

Figure 1. Locations of mines, and access roads in Trill, Drury, Denison and Fairbank townships.

of nickel and copper were extracted, between 1891 and 1897, from the Chicago Mine (Card 1965). At present, only the Crean Hill and Lockerby mines are active. Several companies and prospectors have active mining claims in the study area, including INCO, Falconbridge Limited, Wallbridge Mining Company Limited, Aurora Platinum Corporation, Consolidated Venturex Holdings Limited and P. Maillet. Mining companies have carried out diamond drilling in the area for at least 60 years; in particular, Falconbridge Limited has diamond-drill logs for approximately 60 km of core. Diamond-drilling programs were not reported in the study area during the summer of 2001. Ground and airborne geophysical surveys have been carried out by private companies and also by government agencies over a long time period.

DATA SOURCES

The geology of the Sudbury basin has been studied for more than 100 years, during which time a huge database of information was accumulated. Much of the data are owned by mining companies and are not readily available to the public. Different data sets in the public domain are not necessarily compatible with each other, for instance, not all workers use the same petrologic classifications. Data gathering and synthesis in the study area was performed during the first year of this project and provides the basis of a new, more comprehensive and homogeneous database.

FIELD WORK

Topographic elevation in the study area varies between 250 and 400 m above sea level. The vegetation is no longer as sparse as reported by Card (1965), but numerous areas are not fully covered by vegetation. Outcrops situated on topographic highs (hills, ridges) are composed mainly of granite, gabbro and quartz-rich metasedimentary rocks. Outcrops along the sides of the two main north-south roads,which transect the study area, provide observation points into pelitic metasedimentary rocks that are generally found at lower topographic elevations. Topographic highs and roadside outcrops allow for a regular geographical distribution of observations. All outcrop locations were determined using a hand-held GPS (global positioning system) unit, and geological maps prepared using GIS-based (geographic information system) software (ArcView®).

Figure 2. Photo of survey trail below power line.

In total, 324 outcrops were studied (Figure 3). Approximately one outcrop per 1 km^2 was mapped at 1:50 000, with more detailed mapping concentrated in specific regions. Structural measurements of foliations and lineations, orientations of shear zones, faults and folds were compiled. Sampling at regularly spaced intervals of oriented hand specimens was performed to determine rock types and microstructures. The various styles of sulphide mineralization in the study area were documented and studied.

ACKNOWLEDGMENTS

We would like to thank the Ontario Geological Survey (OGS) for supporting this project under an Ontario Geological Survey–University of Ottawa Collaborative Project Agreement and for providing field logistical support; Falconbridge Limited for allowing us to access their data; and Wallbridge Mining Company Limited for providing accommodations during the field work.

Geological History of the Study Area

The general geology of the study area is shown in Figure 3. The western part of the study area consists of Neoarchean (>2600 Ma) granitic plutons, gneisses, metavolcanic and metasedimentary units of the Superior Province. In the southern part of the study area, Neoarchean rocks are unconformably overlain by metasedimentary rocks of the Paleoproterozoic (2500 to 2219 Ma; Card, Innes and Debicki 1977; Corfu and Andrews 1986) Huronian Supergroup in the Southern Province.

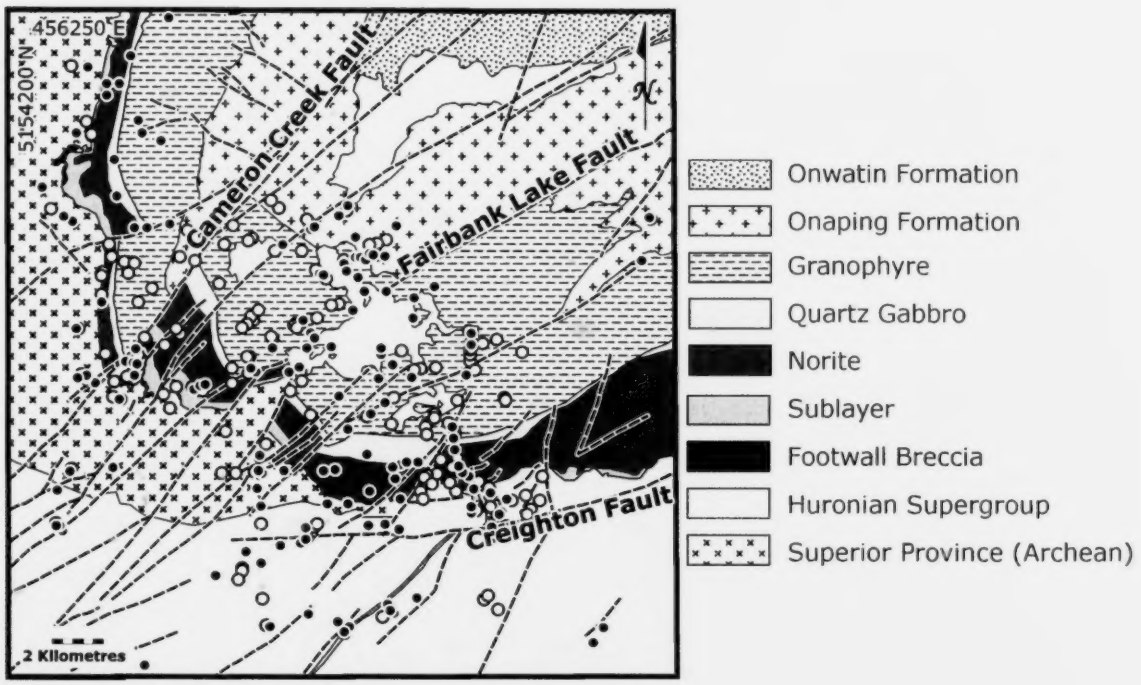

Figure 3. Location of studied outcrops.

The Murray fault zone, which is a major structural feature in the southern part of the Sudbury basin, is thought to have originated as an extensional fault during Huronian sedimentation (Card and Hutchinson 1972). Metasedimentary rocks of the Huronian Supergroup were intruded by plutons of granitic (2388 +20/–13 Ma; Krogh, Davis and Corfu 1984) and anorthositic gabbro (2480 +10/–5 Ma; Krogh, Davis and Corfu 1984). The metasedimentary and metavolcanic rocks of the Huronian Supergroup were folded prior to the intrusion of the Nipissing diabase sills (2219 Ma) (Card 1978, Bennett, Dressler and Robertson 1991).

The Penokean Orogeny, 1890 to 1830 Ma (Van Schmus 1980; Hoffman 1989), affected the Sudbury area. This was a regional, compressional event that resulted in large-scale regional folding and displacements along south-dipping thrust faults (Zolnai, Price and Helmstaedt 1984). The Penokean Orogeny deformed the Huronian Supergroup and reactivated the Murray fault zone as a south-dipping thrust fault (Cooke 1946).

The Sudbury event, a meteorite impact (Dietz 1964) that created the SIC and the Sudbury breccia, has an age of 1850 Ma (Krogh, McNutt and Davis 1982). The SIC is a tripartite magmatic assemblage consisting of norite overlying the footwall breccia at the bottom of the SIC, gabbro and a granophyre magmatic body (Figure 4). The initial shape of the SIC may have been that of a flat-lying tabular impact melt sheet (Grieve, Stoffler and Deutsch 1991). Alternatively, the SIC may have originally had an inverted funnel shape (Shanks and Schwerdtner 1991b).

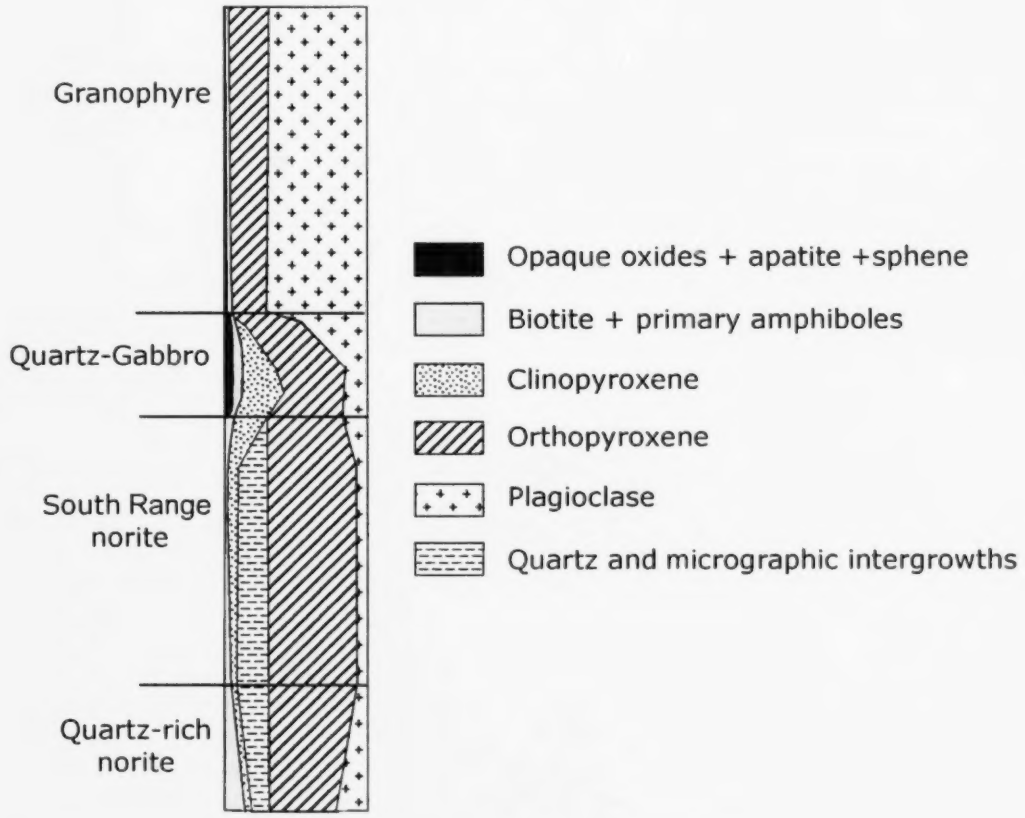

Figure 4. Occurrence of mineral species in the SIC.

A passive magmatic event of granitic plutonism (1750 Ma; Davidson and van Breemen 1994) affected the south of the Sudbury basin (Fueten and Redmond 1997). Subsequently, at approximately 1450 Ma (Shanks and Schwerdtner 1991a), the Sudbury basin underwent another orogenic event that involved southeast-over-northwest ductile thrust faulting. This period of deformation led to the formation of the South Range shear zone (SRSZ) that deformed the southern part of the SIC (Shanks and Schwerdtner 1991a). Ductile thrusting on the SRSZ is thought by Shanks and Schwerdtner (1991a) to have caused the SIC to be deformed into its present elliptical shape. Much of the study area lies within the SRSZ, as defined by Shanks and Schwerdtner (1991a).

The SRSZ is 50 km long by 7 km wide and affects the Onaping Formation and the southern part of the SIC. The SRSZ is bounded in the north by folded rocks of the Whitewater Group, which includes the Onaping, Onwatin and the Chelmsford formations; and, to the south, by virtually undeformed layered rocks of the SIC (Shanks and Schwerdtner 1991a). The SRSZ is expressed by penetratively foliated and lineated rocks. The structure accommodated a large net thrust displacement of approximately 8 km (Shanks and Schwerdtner 1991a). This period of deformation was followed by the emplacement of the Sudbury olivine diabase dike swarm at 1238±4 Ma (Krogh et al. 1987).

The last orogenic phase that affected Sudbury basin was the Grenville Orogeny (1070 to 1000 Ma) (Zolnai, Price and Helmstaedt 1984). Within the Sudbury basin, the Grenvillian orogenic event is characterized by dominant brittle deformation. This deformation event also reactivated the east-northeast-striking Murray fault zone, resulting in right-lateral displacements (Card 1968).

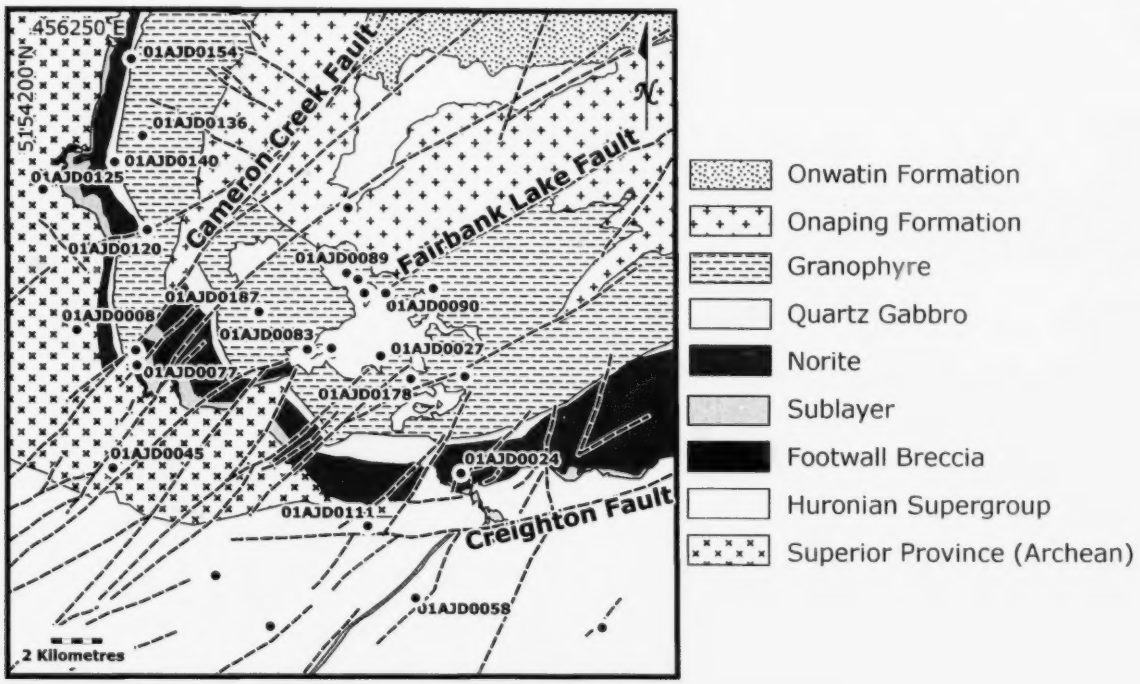

Figure 5. Locations of the samples analyzed by thin section.

Results of the Geological Study

MAJOR ROCK TYPES

At present, 49 thin sections have been analyzed as part of this study (Figure 5) in order to complete the geological map and to observe structural deformation at microscopic scale. Previous workers have already described the petrology of the SIC (Naldrett et al. 1970; Naldrett and Hewins 1984) rocks in the South and North ranges. Petrographic determinations of our thin sections have been done by texture and mineral composition analysis and comparison with previously published descriptions (Naldrett and Hewins 1984).

During the cooling of the SIC, an inclusion-rich layer referred to as the Sublayer, formed between the footwall and the SIC (Morrison, Jago and White 1992). Sublayer outcrops were encountered during this study close to the Victoria Mine and to the Sultana Mine. They are also found discontinuously at the contact between the SIC and the footwall rocks. The matrix is fine- to coarse-grained, noritic to gabbroic rock. Xenoliths of a wide variety are included in that matrix and were derived from the adjacent footwall (Pattison 1979). Xenolith size ranges from a few millimetres to 20 cm. They are strongly sheared and lengthened in only one direction. They display a constrictional deformation . A gradational contact is observed between the sublayer and the overlying norite.

Norite outcrops were observed along the roadside north of the Chicago Mine and south of Fairbank Lake; north of the Victoria Mine and south of Skill Lake; and southwest of Cameron Lake. The norite matrix is medium to coarse grained, dark green to black and consists of cumulus plagioclases and enstatite with intercumulus of quartz, augite, magnetite and ilmenite and may contain amphibole and biotite (Naldrett and Hewins 1984). Principal minerals are plagioclase (up to 50%), augite (<2%), orthopyroxene (enstatite) (10%), biotite and primary amphibole (ferro- and magnesio-hornblende) (Figure 6). The lower part of the norite is quartz rich (5 to 20% of the volume) (Naldrett et al. 1970; Naldrett and Hewins 1984), whereas the upper part contains less than 5% quartz (*see* Figure 4). A gradational contact is observed between the norite and the overlying quartz gabbro unit.

In hand specimen, quartz gabbro looks like norite but with more quartz. The quartz gabbro is dark grey to black, coarse grained and composed of plagioclase (40%), augite (5%), hornblende (15%) and biotite (20%) (Figures 4 and 7). Micrographic intergrowths are common (up to 20% of the interstitial phase). Plagioclase crystals are subhedral to euhedral prismatic, lath shaped and 0.5 to 3.0 mm in length. Toward the top of the quartz gabbro, crystals of plagioclase may have a rectangular habits. Clinopyroxene (augite) crystals are subhedral to anhedral prismatic, lath shaped and 0.1 to 3.0 mm in length. Quartz gabbo outcrops have been mapped southwest of Cameron Lake and south of Skill Lake. The contact between the quartz gabbro and the overlying granophyre is also gradational.

Granophyre outcrops are found around Fairbank, Cameron and Skill lakes. On most outcrops, a strong foliation is observed. The granophyre is coarse grained, compositionally heterogeneous and apparently unlayered. It is composed mainly of micrographic and granophyric intergrowths (*see* Figure 4; Figures 8 and 9). The lower part of the granophyre is light pink and coarse grained with a cumulate texture and abundant micrographic and granophyric intergrowths. Epidote (5 to 10%) and primary biotite crystals are also present in the lower granophyre. The middle part of the granophyre is grey and characterized by an increase in chlorite content (10 to 15%), primary biotite and oxide minerals (Therriault 2001). The upper part of the granophyre is medium grained and pink and contains very abundant micrographic and granophyric intergrowths (60 to 65%). The contact between the granophyre and the overlying layer, the Onaping Formation, is not easy to determine. At the contact zone, in some places, the Onaping Formation sinks into the granophyre and, at other places, the granophyre is found surrounded by the Onaping Formation.

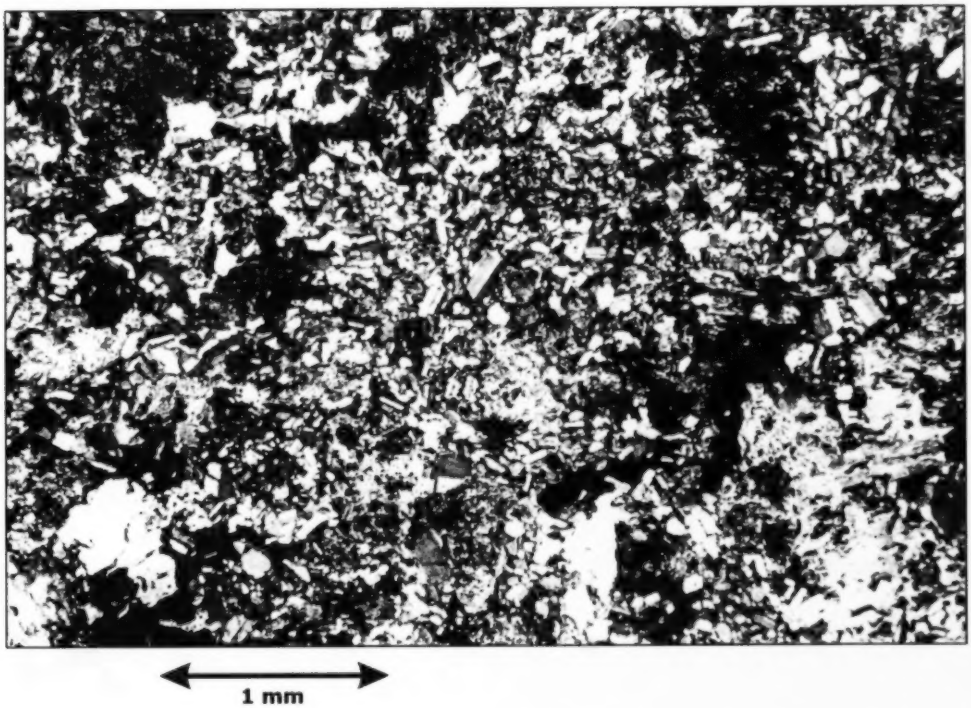

Figure 6. Photomicrograph of a thin section of sample 01AJD77B, a norite, taken with crossed polars.

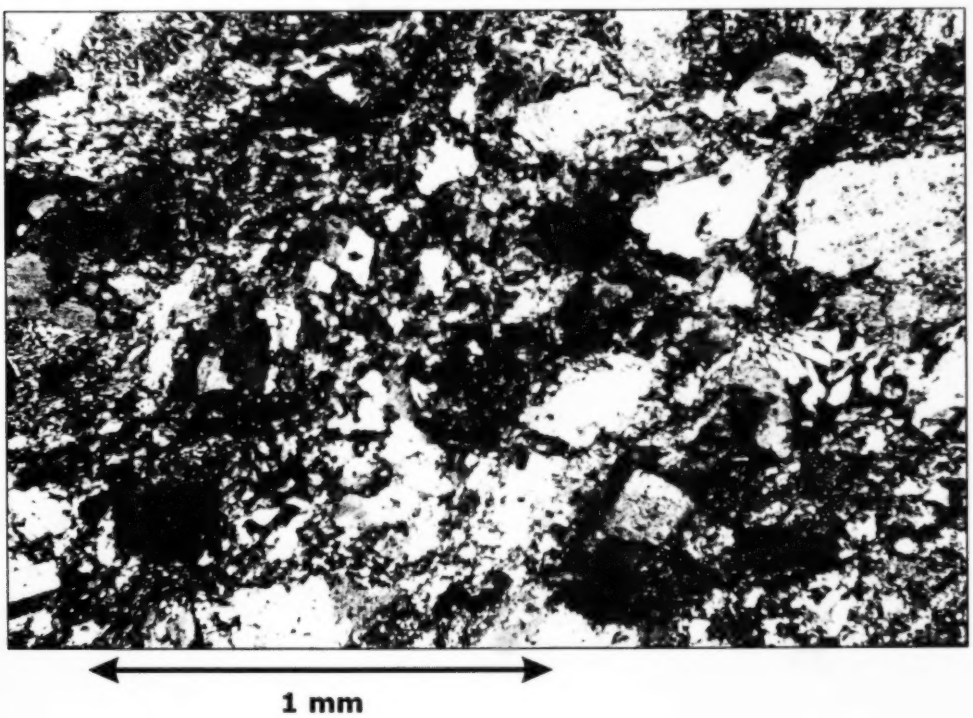

Figure 7. Photomicrograph of a thin section of sample 01AJD27, a quartz gabbro.

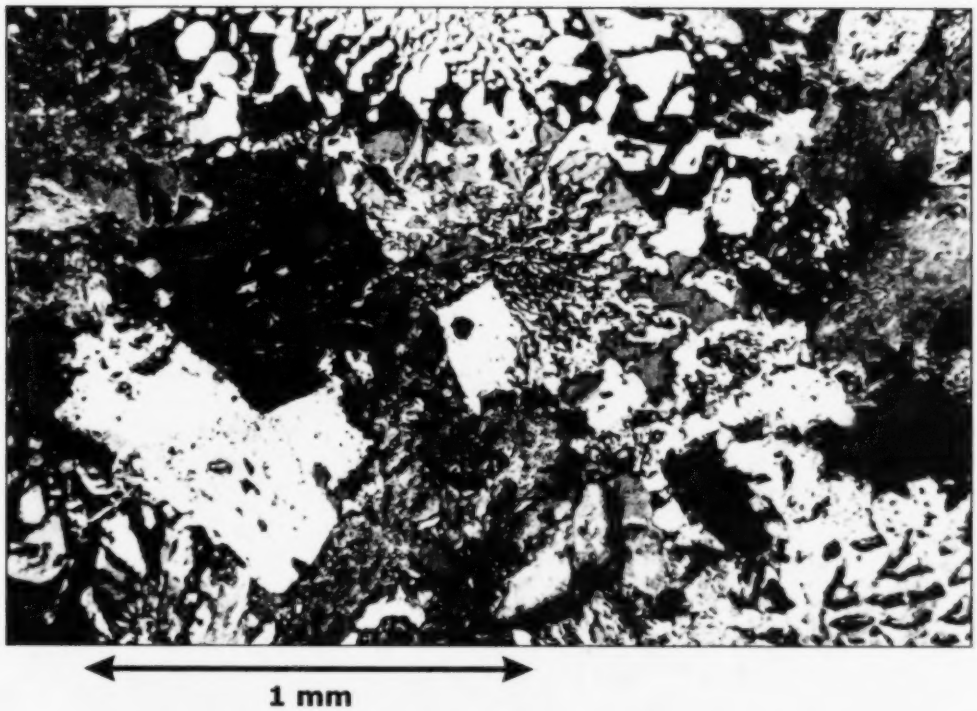

Figure 8. Photomicrograph of a thin section of sample 01AJD154A, a granophyre.

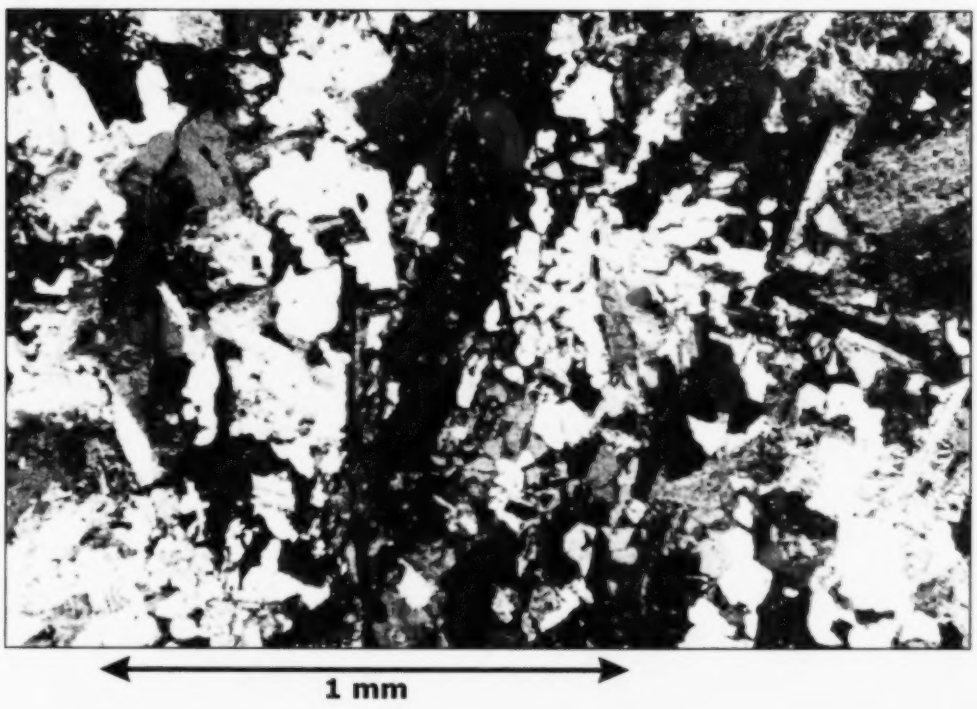

Figure 9. Photomicrograph of a thin section of sample 01AJD140A, a middle granophyre.

Structural Geology

Structural features in 5 separate areas were studied in detail (Figure 10): 1) south of Mosquito Lake; 2) the area around Cameron Lake; 3) 2 areas around the western part of Fairbank Lake: north and south of the Fairbank Lake fault; and 4) the area surrounding Skill Lake. Together, the 5 areas represent a section perpendicular to the Fairbank Lake fault, the major fault in the study area.

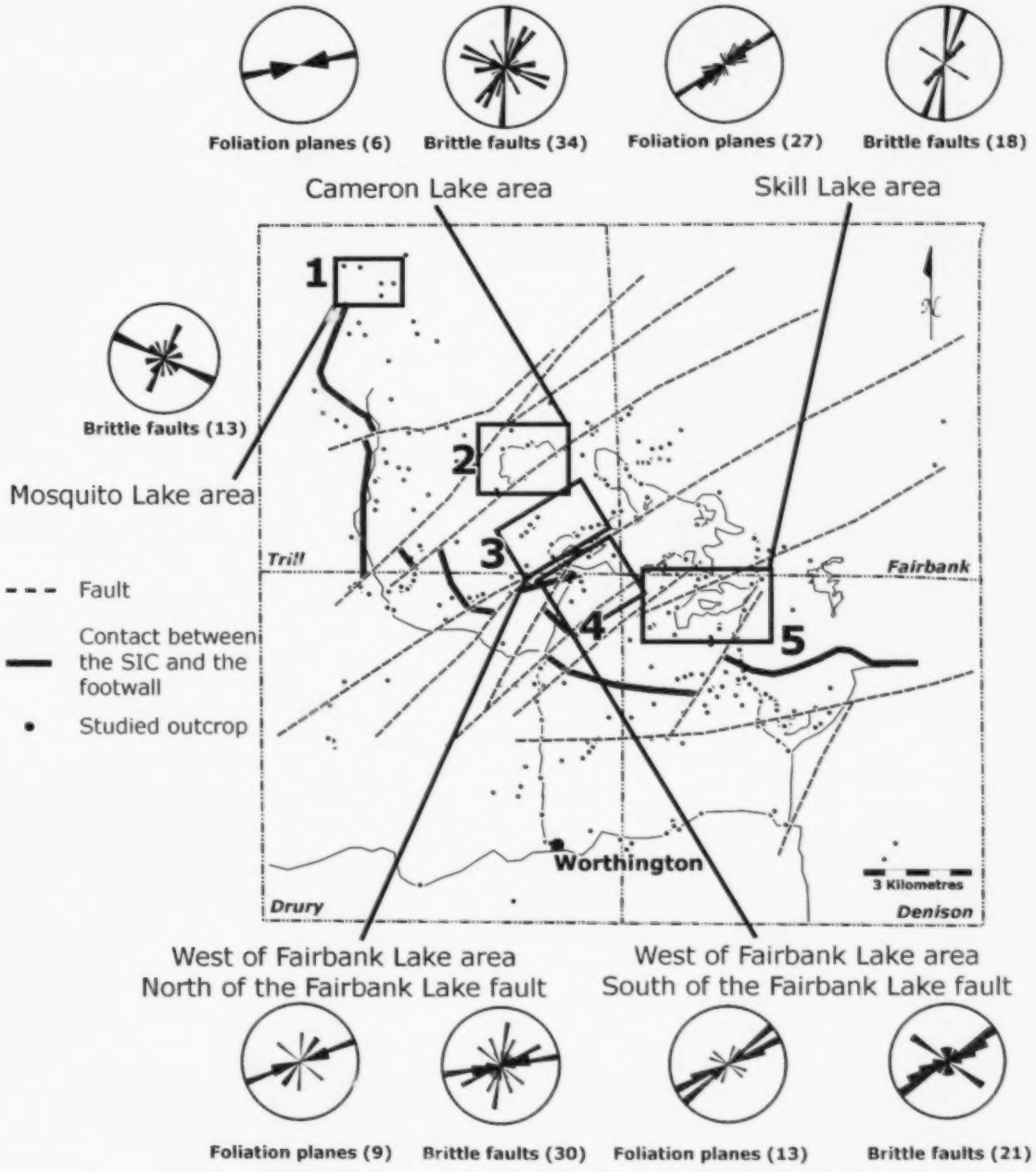

Figure 10. Rose diagrams of foliation strikes and fault strikes.

BRITTLE DEFORMATION

Brittle faulting is ubiquitous in the study area. The brittle faults can be grouped into 3 main orientations: north-northeast-, northeast- and southeast-striking. All 3 groups are present in the 5 areas that were studied in detail; however, it appears that any one of the groups may be dominant in each area. It is likely, that in the strongly foliated rocks near the Fairbank Lake fault, the predominance of northeast-striking faults is related to reactivation of the foliation during brittle faulting. Field observations of slickensides and striations on fault planes indicate that normal, strike-slip and thrust kinematics were accommodated by different faults.

Area 1

The Mosquito Lake area is located north of the Fairbank Lake fault and includes the southern part of Mosquito Lake. Seven outcrops were studied where no evidence of ductile deformation was observed. Brittle faults are present and can be divided into two main groups based on their orientations: a group southeast-striking faults and a group of northeast-striking faults. None of the observed faults host sulphide mineralization.

Area 2

The Cameron Lake area lies along the Cameron Lake fault, a major structure that strikes 055°. Eight outcrops were studied in this area. The rocks are strongly fractured and contain many quartz veins as well as epidote in some places. The penetrative foliation strikes parallel to the Cameron Lake fault. Brittle faults documented in the outcrops can be sorted into 3 main groups according to their orientations: north-northeast, northeast and southeast. All 3 groups have fault breccias preserved within the fault planes. Fault breccia in the southeast-striking faults present a dusty red colour and epidote mineralizations probably link with hydrothermal activity (Figure 11).

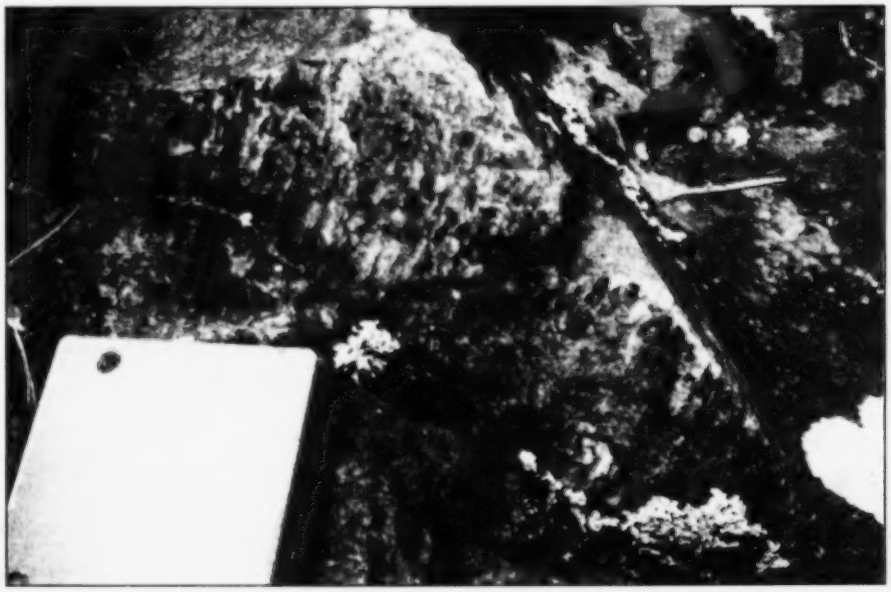

Figure 11. Photo illustrating hydrothermal alteration on a fault plane.

Area 3

Ten outcrops were studied in the area west of Fairbank Lake and north of the Fairbank Lake fault. Foliation planes are parallel to the trace of the Fairbank Lake fault and average 070°. Many fault planes have developed in foliation planes and have exploited the foliation as a plane of mechanical weakness. However, the predominant orientation of brittle faults is 080°, oblique to the foliation and the Fairbank Lake fault. The north-northeast-striking faults are the most abundant faults, which is similar to the Cameron Lake area. Those north-northeast-striking faults present, at some outcrops, quartz mineralization on their fault plane. Only a few fault planes that strike 155° show evidence of a red dusty colour alteration.

Area 4

Eight outcrops were studied south of the Fairbank Lake fault. Here also, the foliation is predominantly parallel to the Fairbank Lake fault (070°). Brittle faults are either northeast or southeast striking. Few faults were documented with the north-northeast strike that is common in the other areas described here. In this area, a red dusty colour alteration was found only on northeast-striking fault planes.

Area 5

Seventeen outcrops were studied in the Skill Lake area. The foliation planes are predominantly parallel to the Fairbank Lake fault (070°). Numerous quartz veins were observed within the foliation planes and quartz veins that strike 040°, that is to say oblique to the foliation, are commonly folded. This is possibly due to transposition of the veins during ductile deformation. Brittle faults occur in the following 3 orientations: north-northeast, northeast and southeast striking. Epidote is present on several outcrops and a red dusty colour alteration on the north-northeast-striking fault planes.

Analysis of the stress fields associated with faulting was carried out using software developed by Ramsay and Lisle (2000). The program performs a grid-search method of stress inversion from fault slip data. Results show a northwest maximum compression direction (Figure 12). This suggests that brittle faulting may possibly record northwest shortening of the Sudbury basin during the Grenville Orogeny. On every outcrop, there is no relation between a particular fault orientation and a specific hydrothermal alteration. The alteration affects every fault plane present, so, it is probably a late event.

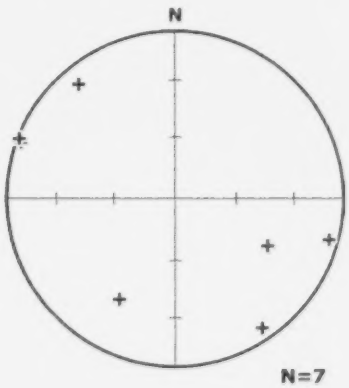

Figure 12. Maximum compression (*senus lato*) direction determined on 7 outcrops by inversion of striation orientations on fault planes (lower hemisphere equal-area projection). The maximum compression direction strikes northwest-southeast and is almost horizontal.

DUCTILE DEFORMATION

Ductile deformation elements were observed on 324 outcrops distributed in Trill, Denison, Fairbank and Drury townships. Outcrops are located on both sides of the Fairbank Lake fault, which is the northern limit of the SRSZ according to Shanks and Schwerdtner (1991a). Information collected from these outcrops is displayed in Figures 10 and 13.

Within the SRSZ, ductile deformation is strongly expressed and commonly manifested as quartz veins that are folded and transposed into the foliation planes (Figure 14). Some quartz veins range in thickness from centimetres to decimetres and display a dextral sense of shear on foliation planes when observed on horizontal outcrop surfaces (*see* Figure 12). On vertical outcrop surfaces in the SIC, sheared clasts of quartz in the foliation plane indicate a south-over-north displacement associated with the development of the foliation. Study of thin sections, that contain C/S microfabrics (Figures 15 and 16), confirms the south-over-north displacement. Hence, the development of the strong, penetrative fabric was associated with an oblique, reverse-dextral displacement of the hanging-wall block (south of the SRSZ) over the footwall block (north of the SRSZ). Evidence for ductile deformation can be observed in

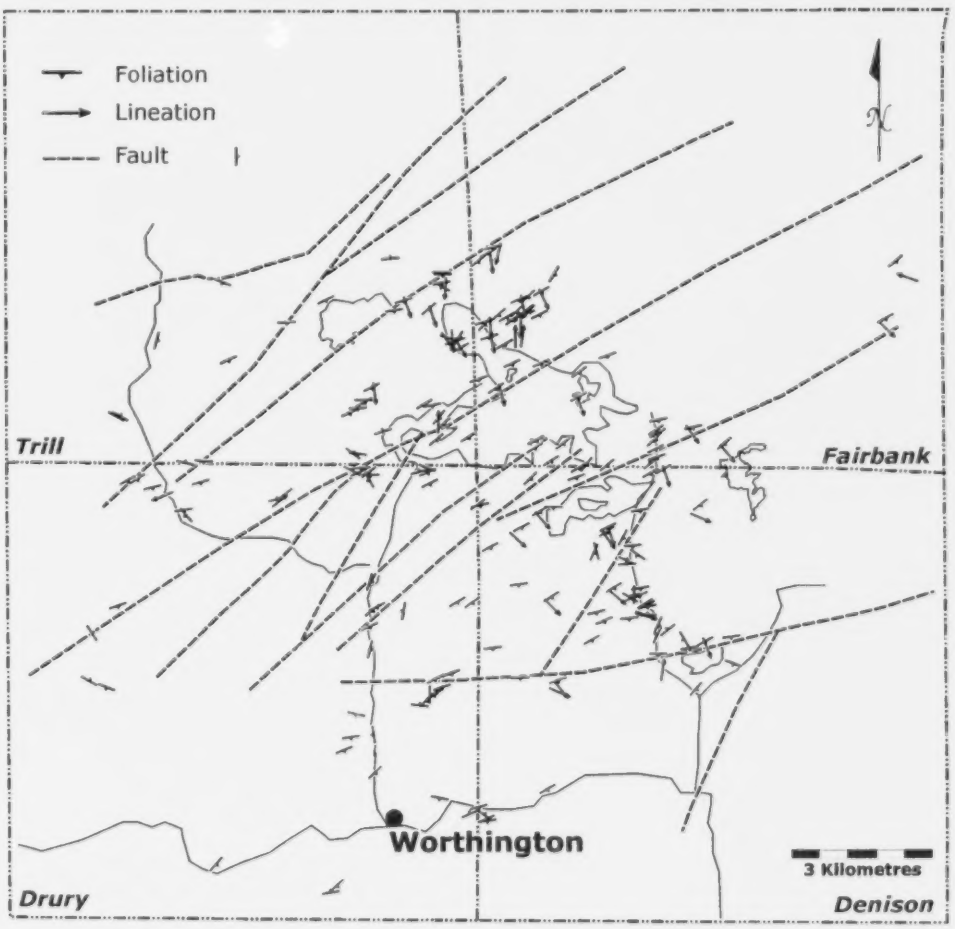

Figure 13. Ductile deformation elements in the study area.

footwall rocks, in the SIC and in the southern part of the Onaping Formation. In some outcrops, a strong constrictional fabric is observed, i.e., clasts are highly elongated, defining a strong lineation, but the foliation is poorly developed or absent (Figure 17). This observation is important because on horizontal outcrop surfaces, which are at a high angle to the extension lineations, the rocks with highly constrictive fabrics may appear to be undeformed.

The ductile fabric in the study is poorly developed or absent 10 km north of the Fairbank Lake fault, north of the northern limit of the SRSZ. Within the SRSZ, the foliation strikes predominantly northeast to east-northeast, with a consistent strike direction with only minor variations. The strike of foliations are similar to the trend of major faults in the western Sudbury basin. Presumably, the penetrative foliation records the ductile thrusting that was accommodated on the SRSZ (Shanks and Schwerdtner 1991a). Differences in the orientation of ductile fabrics, from area to area, may record differential rotations of blocks during later brittle faulting. This hypothesis remains to be verified.

Figure 14. Photo showing asymmetrical sheared quartz vein oblique to the foliation.

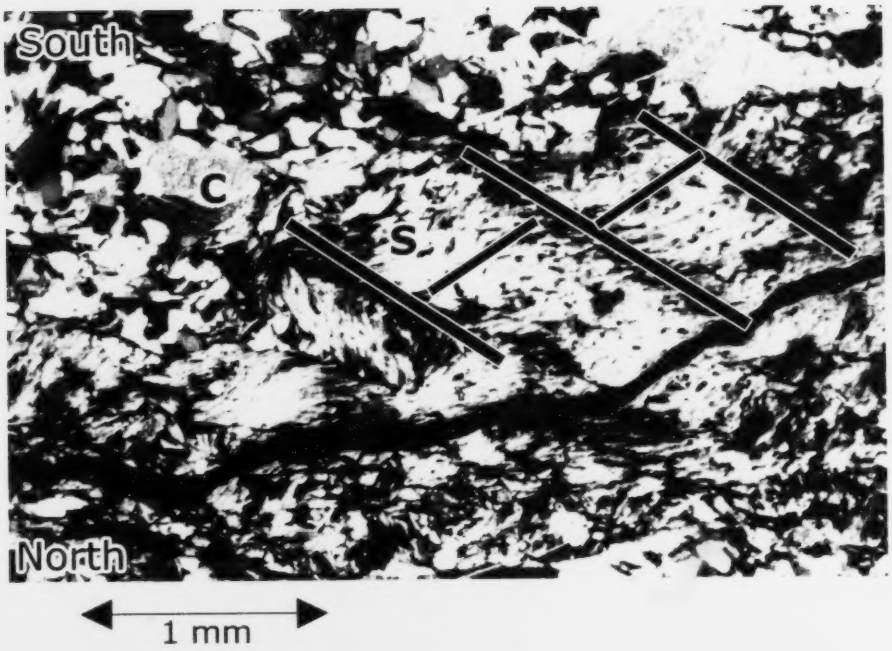

Figure 15. Photomicrograph of a thin section of sample 01AJD24A (greenstone), taken with crossed polars. The C/S structure observed in chlorite displays a south-over-north displacement.

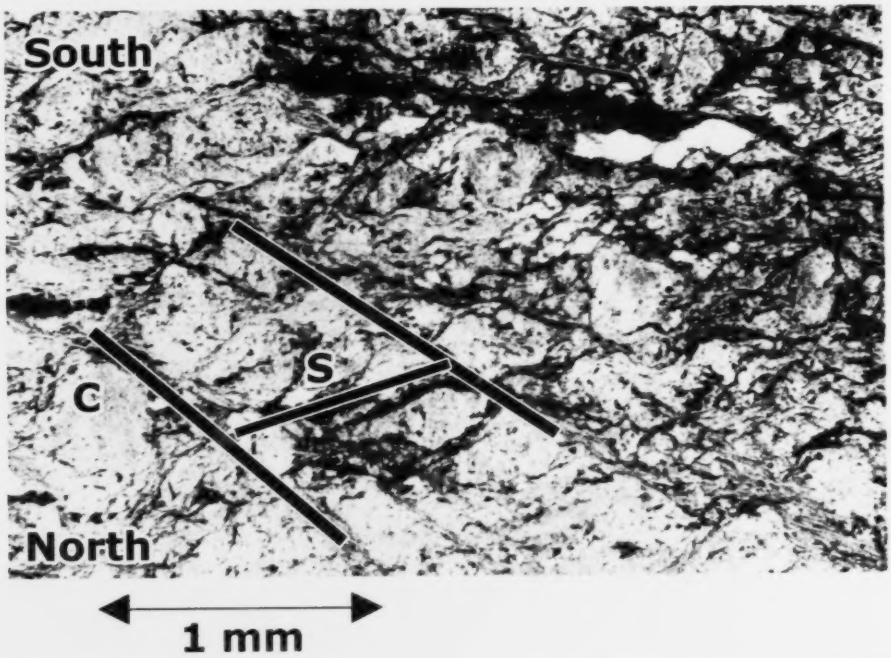

Figure 16. Photomicrograph of a thin section of sample 01AJD89B (granophyre), in plane-polarized light. The C/S structure displays a south-over-north displacement.

Figure 17. Photos of 2 hand specimens. The one on the left comes from the sublayer unit and was collected at the Victoria Mine. The one on the right was collected in the Onaping Formation, north of Fairbank Lake. Clasts on these 2 hand specimens record a constrictive deformation.

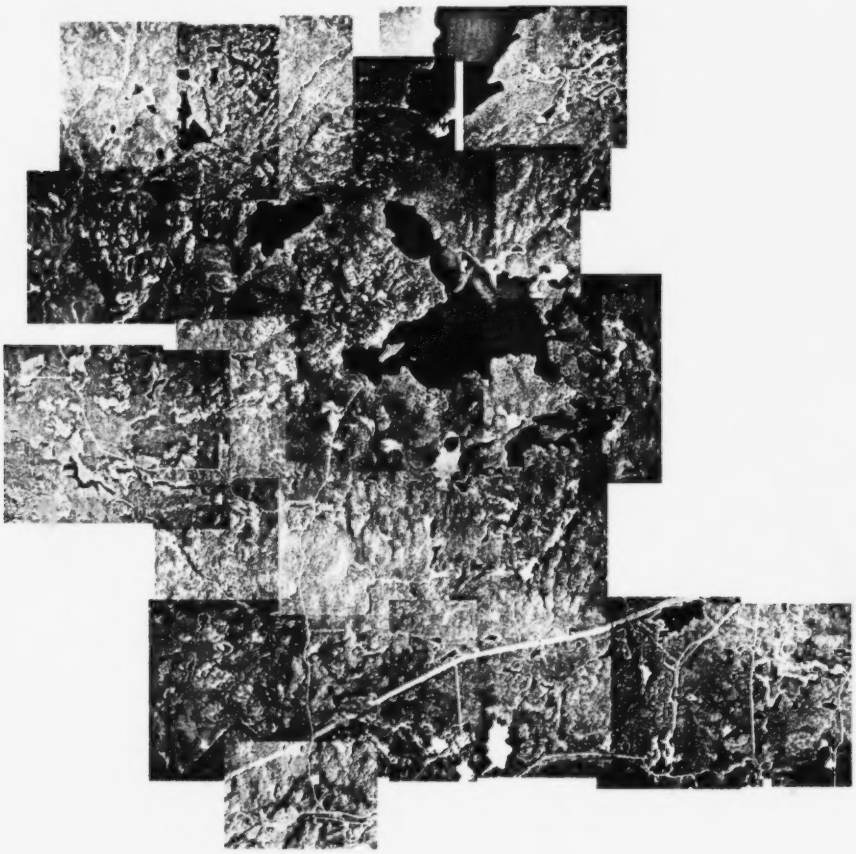

Figure 18. Aerial photo mosaic of the study area.

The southern limit of the SRSZ remains poorly defined in the study area. However, in the southern part of the area a few kilometres south of Skill Lake and south of the Creighton fault (*see* Figure 9), the rocks occur within the hanging-wall block of the SRSZ. In the hanging-wall block, the rocks are deformed by systems of abundant outcrop-scale (and larger scale?) anastomosing shear zones. The shear zones are steeply dipping to vertical and the extension lineations and striations within them are in the dip (subvertical). This suggests a bulk pure shear with a vertical maximum principal stretch. Interestingly, sulphide mineralization seems to have a positive spatial relationship with the anastomosing shear zones. The deformation state in the hanging wall is distinct from the rocks within the SRSZ, for example, the homogeneous structure and microstructure, in proximity to the Fairbank Lake fault, indicates that the SRSZ is a dextral-reverse sense shear zone.

Aerial photographic coverage of the study area consists of 2 surveys, one in 1973, the other in 1977. An aerial photo mosaic of the whole area (Figure 18) has been prepared to assist in the interpretation of structural observations at the regional scale using stereoscopic views. The stereoscopic analysis is still in progress.

A Working Model

Data and observations gathered during the first 9 months of this project allow us to propose a working model for the post-Sudbury event structural evolution of the western Sudbury basin. Our working model involves thrust imbrication in a transpressive setting. In transpression, strain may be partitioned into 1) predominantly simple shear, concentrated within shear zones and/or faults that are more or less parallel to the bulk regional shear displacements; and 2) predominantly bulk pure shear within intervening blocks of rock. In terranes where horizontal layering is present, the bulk pure shear may be accommodated by *en échelon* folding with axial surfaces striking less than 045° to the regional shear zones and faults. Such a deformation style might be represented by the folds within the layered units that overly the SIC (i.e., Whitewater Group; Shanks and Schwerdtner 1991).

In our working model, we interpret that simple shear may have been partitioned into the regional shear zones and faults, like the Fairbank Lake fault, where the deformation state is quite homogeneous and shear sense indicators record dextral-reverse displacements.

In the study area, bulk shortening pure shear is recorded by the systems of anastomosing shear zones, for example, in the hanging-wall block of the SRSZ. The shear zones affect parts of the SIC as well as the metamorphosed Huronian Supergroup rocks of the footwall. The abundant outcrop-scale (and larger-scale?) anastomosing shear zones are steeply dipping with vertical extension lineations and striations within them. We interpret that bedding in metamorphosed Huronian Supergroup strata was tilted to steep dips before the deformation event related to the SRSZ. The steep dips of the bedding, possibly inherited from pre-Sudbury event deformation, would have precluded the development of regional-scale folds in the Huronian Supergroup rocks during later north-south horizontal shortening. Therefore, the Huronian Supergroup rocks accommodated the regional post-Sudbury event bulk shortening by the development of the shear zones. Interestingly, some sulphide mineralization seems to have a positive spatial relationship with the anastomosing shear zones, suggesting possible remobilization of sulphide mineralization during post-Sudbury event deformation.

There is also abundant structural evidence for extensional faulting in the SIC, in the overlying Onaping Formation and in the footwall rocks. Some extensional faulting likely occurred during relaxation of tectonic stresses, late in the thrusting history in the basin. At least locally, some sulphide mineralization is associated with normal faults in the lower part of the SIC.

THREE-DIMENSIONAL MODELLING

We have gathered structural field observations, petrographic information on hand samples and thin sections, diamond-drill core descriptions and geophysical data. Falconbridge Limited possesses diamond-drill logs for the study area that represent a total of 62 km of drill core. So far, we have studied the logs, provided by Falconbridge Limited, for 26 diamond-drill holes (Figure 19) that correspond to 12 km of core. The selected cores are from diamond-drill holes that were collared on lake shores (Fairbank Lake, Ethel Lake and Bass Lake) and on former mining sites (Chicago Mine, Crean Hill Mine and the Sultan Mine). Drill core data have been compiled into CAD drawing files (Figure 20) that will be used to construct vertical cross-sections in order to constrain three-dimensional models.

Further field work and investigation of diamond-drill core was conducted during the summer of 2002. All those data will be used to construct geological profiles and three-dimensional models of the study area. Also, a software package will be used to test possible three-dimensional kinematic models for the deformation of the western Sudbury basin. These models should provide valuable constraints on the subsurface geology and also on the original form of the basin and the SIC.

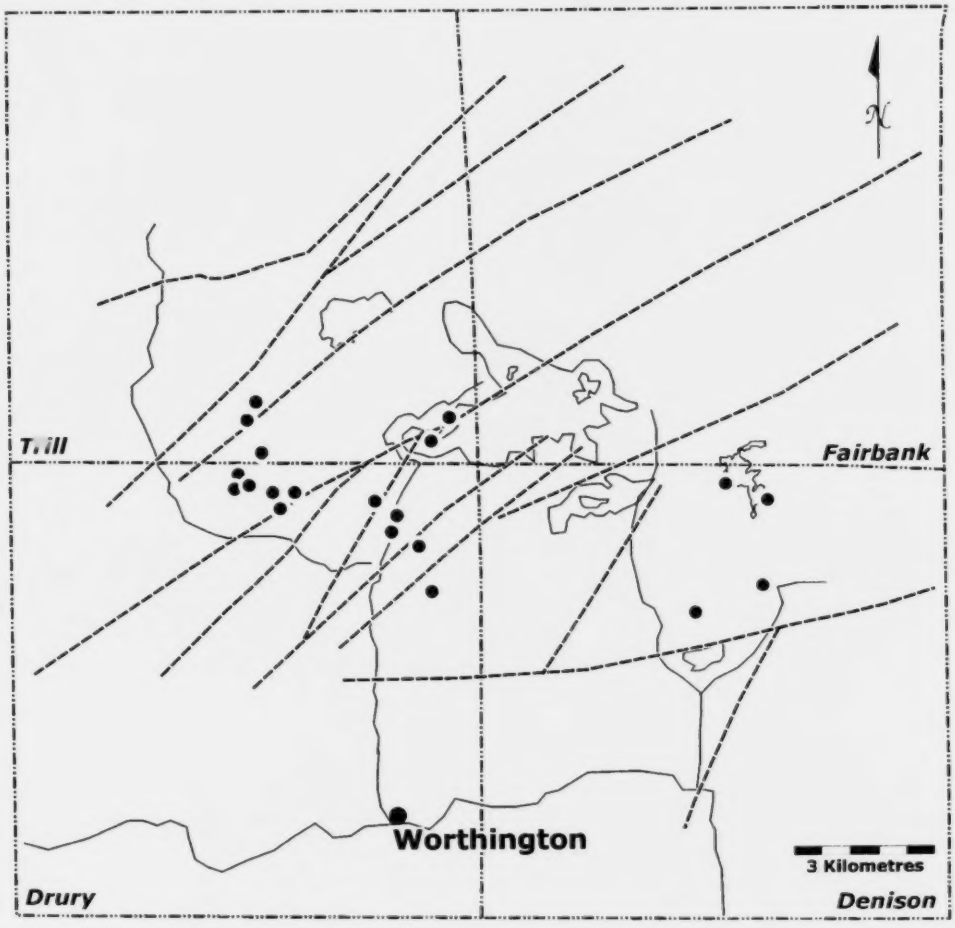

Figure 19. Location of studied drill holes, logs for which were provided by Falconbridge Limited.

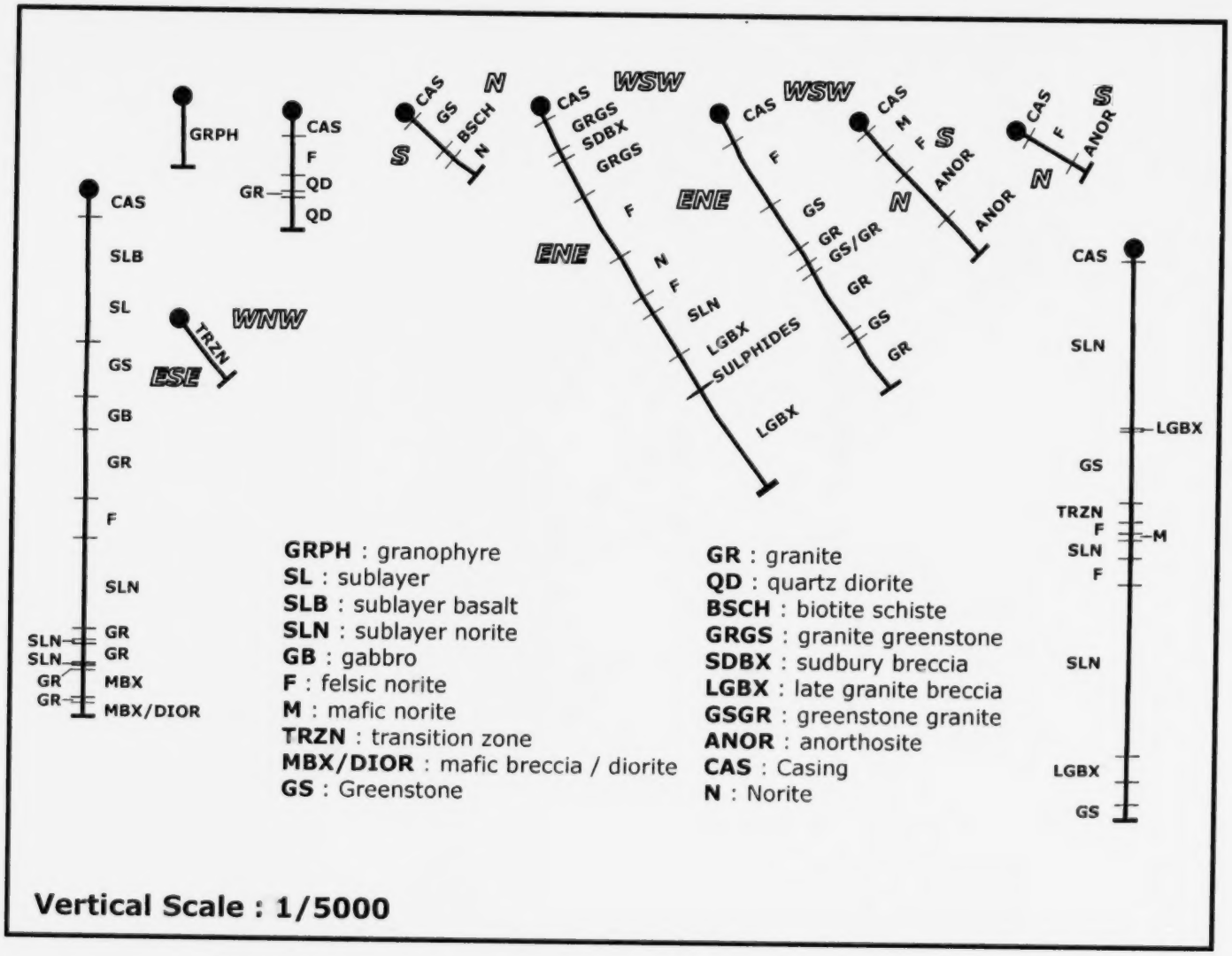

Figure 20. Vertical cross-sections constructed using drill-core data provided by Falconbridge Limited.

SOFTWARE

The Noddy™ software package has been chosen to for the three-dimensional modelling. This software deals with a 3D-block, the size of which can vary from 50 by 50 by 50 m^3 to 9000 by 9000 by 9000 km^3, which is more than enough to model the study area. This 3D-block is composed of cubic cells with variable sizes, and the chosen cell size defines the accuracy of the model. An edge of the cell may range from 50 m to 1 km.

Geometrical, lithologic and petrophysical characteristics (rock properties) of the modelled rocks may be integrated. The modelling process involves choosing a possible pre-deformational configuration for the study area, including its geometrical and compositional makeup and pre-existing structures, and imposing a deformational history on the modelled rock body. The resulting model may be tested by 1) generating three-dimensional blocks that can be compared to the known surface and subsurface geology; and 2) by generating geophysical maps from model results using the petrophysical properties of the rocks in the study area (e.g., densities, magnetic properties). Some examples are shown for a hypothetical three-dimensional model in Figures 21 to 25. Those figures illustrate the forward modelling of a three-dimensional block and the generation of the resulting geophysical maps. The software can also generate artificial drill-holes based on the model results.

PETROPHYSICAL PROPERTIES

The SIC is located at the boundary between the Archean Superior Province, to the north, and metamorphosed Proterozoic (Huronian Supergroup) rocks to the south. The Archean rocks consist of granitic plutons, gneisses and greenschist-facies metavolcanic and metasedimentary rocks. The Huronian Supergroup rocks consist of metasedimentary and metavolcanic rocks intruded by granitic plutons and anorthositic gabbro. The SIC is a tripartite magmatic assemblage consisting of norite overlying the footwall breccia at the base of the SIC. The Onaping Formation, interpreted to be a fall-back breccia resulting from the meteor impact (Beales and Lozej 1975), overlies the granophyre of the SIC.

Densities of those rocks have been determined by Gupta, Grant and Card (1984) and McGrath and Broome (1992), but we will use the data from the latter (Table 1) in our three-dimensional models as McGrath and Broome (1992) have homogenized their data with those from Gupta, Grant and Card (1984). Based on earlier work by Morris (1984), Hearst, Morris and Thomas (1992) summarized the magnetic properties of rocks in the Sudbury basin and these data are in Table 1.

Table 1. Petrophysical properties of the different lithologies.

	Densities ($g \cdot cm^{-3}$)[1]	**Magnetic Characteristics**[2]
		Susceptibility observed ($\times 10^{-6}$ SI)
Chelmsford Formation	2.75	10
Onaping Formation	2.77	Between 10 and 150
Granophyre	2.70	25
Norite	2.81	60
Huronian Supergroup (metasedimentary rocks)	2.70	10
Huronian Supergroup (mafic intrusion)	2.88	20
Archean gneiss	2.77	Between 200 and 850

[1] McGrath and Broome (1992)
[2] Hearst, Morris and Thomas (1992)

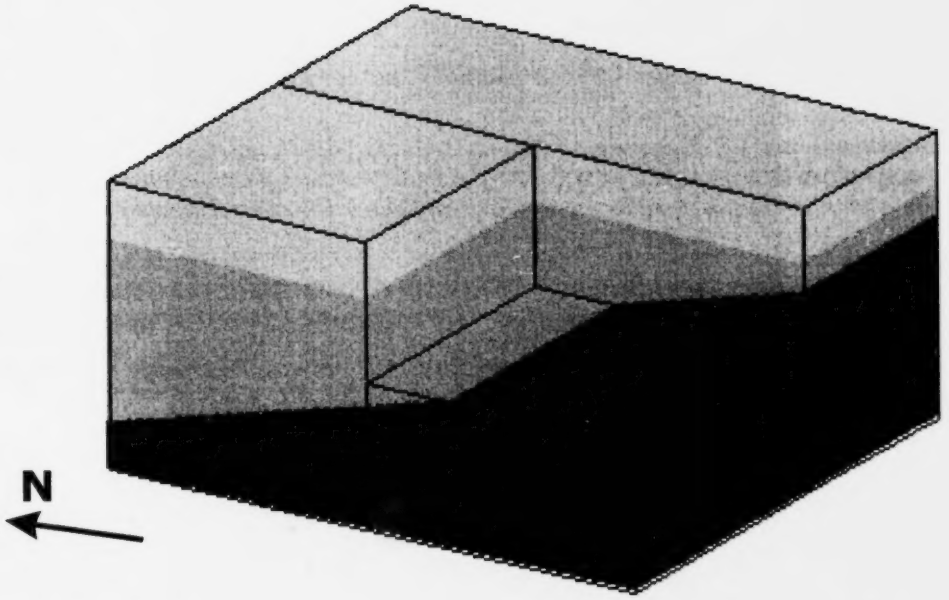

Figure 21. Geological model constructed with Noddy™ software. This arbitrary model presents 2 horizontal layers lying unconformably on 2 other horizontal layers.

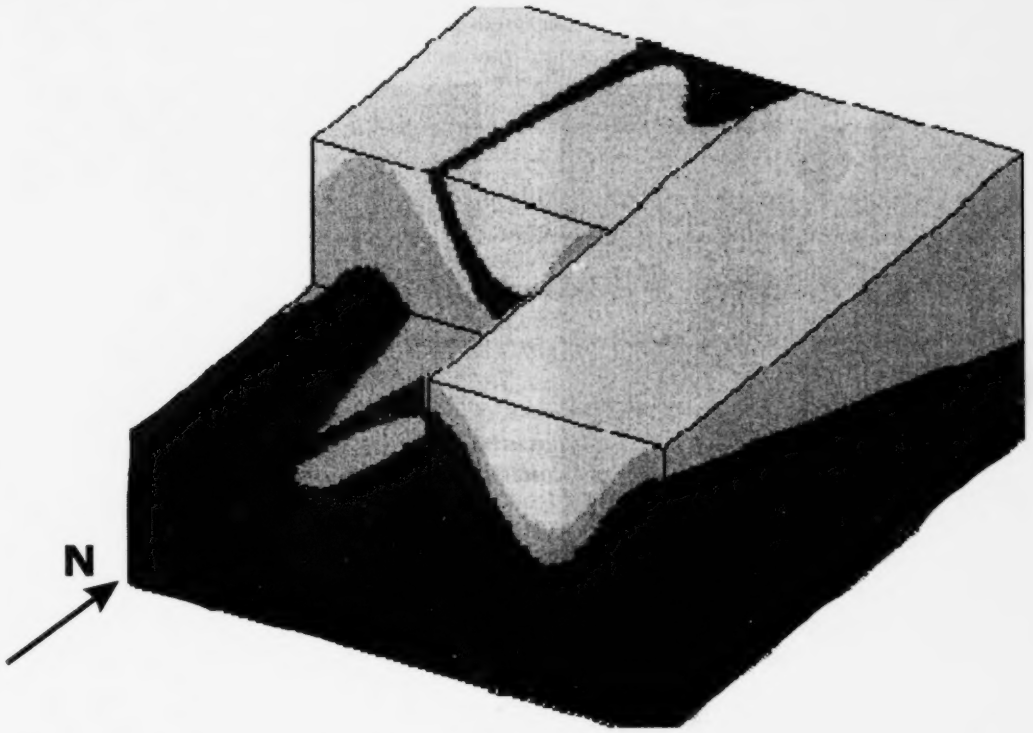

Figure 22. Geological model constructed with Noddy™ software. Same block as shown in Figure 21 after the intrusion of a dike and a folding stage of deformation.

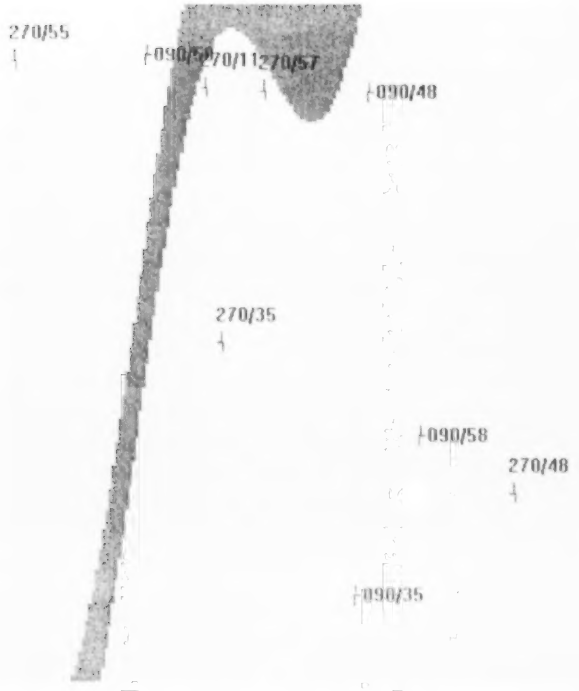

Figure 23. Geological map constructed with Noddy™ software. This geological map corresponds to the block shown in Figure 22.

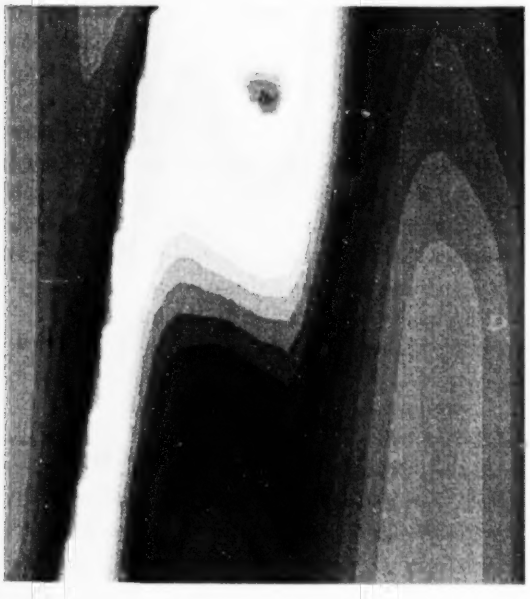

Figure 24. Gravity anomaly map constructed with Noddy™ software. This gravity anomaly map is determined from the block shown in Figure 22 and with the densities of the layers entered into the software.

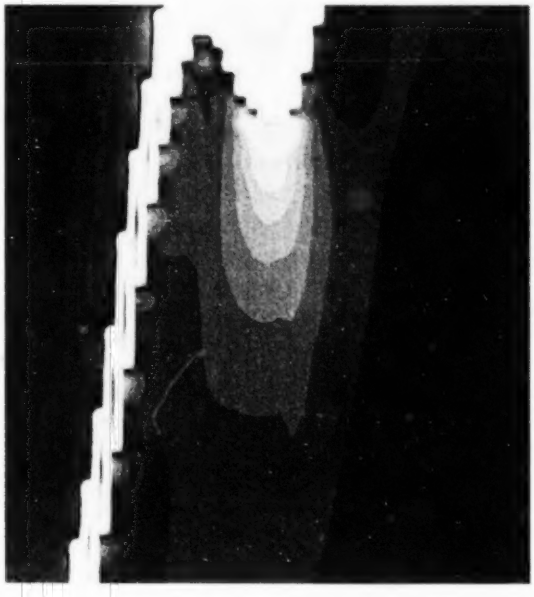

Figure 25. Magnetic anomaly map constructed with Noddy™ software. This magnetic anomaly map is determined from the block shown in Figure 22 and with the magnetic properties of the layers entered into the software.

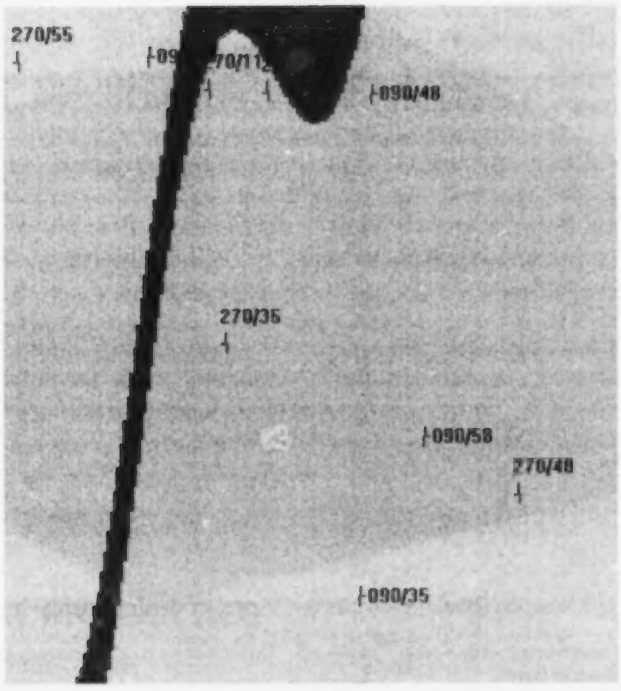

Figure 23. Geological map constructed with Noddy™ software. This geological map corresponds to the block shown in Figure 22.

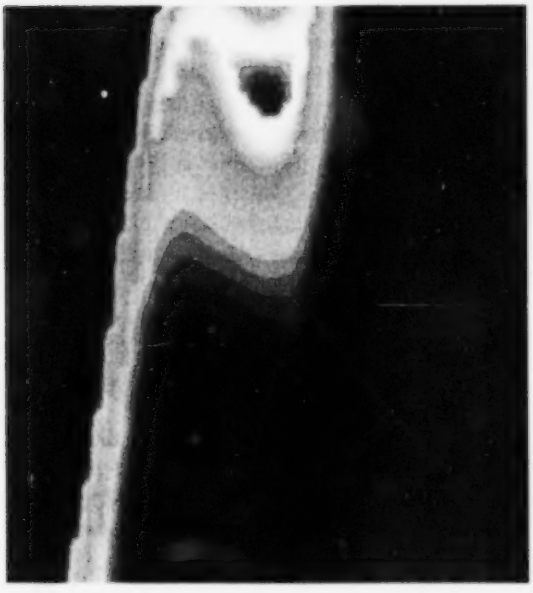

Figure 24. Gravity anomaly map constructed with Noddy™ software. This gravity anomaly map is determined from the block shown in Figure 22 and with the densities of the layers entered into the software.

Figure 25. Magnetic anomaly map constructed with Noddy™ software. This magnetic anomaly map is determined from the block shown in Figure 22 and with the magnetic properties of the layers entered into the software.

Implications for Mineral Exploration

The study area is the most structurally complex part of the Sudbury basin. Successful mineral exploration programs should therefore benefit from the extensive structural analyses that are part of this study. The results will improve the available constraints on the structural evolution of the study area and on the geometries of the different rock units and major structures in the subsurface. The resulting information from the structural analysis will provide a new framework for mineral exploration in the western part of the Sudbury basin.

The compilation of an extensive database will include the results of mapping and structural analysis; data gleaned from extensive studies of diamond-drill core; and the incorporation of available geophysical data. This will provide the basis for three-dimensional modelling of the subsurface geology and modelling of the structural evolution of the study area. The types of ore bodies exploited within the Sudbury basin are well known and documented (Morrison, Jago and White 1992) and include

1. contact deposits associated with the Sublayer and situated within apparent depressions at the base of the SIC;
2. Offset dike deposits that are exploited within the quartz-dioritic dikes that are interpreted to be impact melts injected into fractures in the footwall rocks; and
3. footwall ore bodies that are interpreted as differentiates of the contact ore bodies.

Other ores may have been generated by post-impact hydrothermal events that remobilized and concentrated metals within the Sudbury breccia (Watkinson 1994). The Noddy™ software package will allow us to incorporate the petrophysical properties of orebodies, and the shape of known orebodies, into the three-dimensional models. In this way, new constraints will be derived for the formation of the orebodies and their subsequent modification by deformation. Furthermore, the modelling may lead to the identification of geophysical anomalies that may represent unidentified exploration targets.

Conclusions

During the first summer of field work, in 2001, over 300 outcrops were mapped and extensive sampling was carried out for petrographic studies. Bedrock mapping (Figure 26, back pocket) and preliminary petrographic results lead us to recognize 3 structurally distinct zones within the study area. Detailed mapping around Mosquito Lake does not display strongly sheared rocks that represent the SRSZ. The South Range shear zone (SRSZ) starts further south of Mosquito Lake area, around Cameron Lake. The southern limit of the SRSZ may correspond to the Creighton fault, an interpretation that will be tested by further field work. Structures, south of the SRSZ, suggest a bulk pure shear with a vertical maximum principal stretching direction. This structural framework suggests that post-Sudbury event ductile deformation, in the study area, may have occurred in a 1) transpressive regime with simple shear partitioned into dextral-reverse shear zones (within the SRSZ); and 2) bulk pure shear partitioned within the hanging-wall block of the SRSZ.

Detailed studies of diamond-drill core have been undertaken and data from drill logs will be used to establish structural profiles in key parts of the study area. In 2002, the data collected from bedrock mapping, the diamond-drill hole logs and available geophysical data were used to constrain the geometries of the rocks and structures in the subsurface. Structural modelling software was then used to test possible kinematic models to explain the post-Sudbury event deformation in the western Sudbury Basin. These results will be published in a future report.

The results of the extensive mapping, petrographic studies, drill core logging and structural modelling should provide a new framework for targeting potential mineral exploration targets, and also for proposing models for the formation, and subsequent deformation of the Sudbury impact structure and its hosted mineral deposits.

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Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

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